Statistical Problems in Ocean Modeling and Prediction

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LONG-TERM GOALS

My project addresses statistical problems in the following fields: Lagrangian prediction and Lagrangian data assimilation (1), estimating transport and mixing parameters from tracer observations (2), and ocean model validation (3). The long range scientific goals of this study comprise determining limits of predictability for Lagrangian motion in semi-enclosed seas and littoral zones on time scales of days and weeks, estimating mixing and transport parameters in the upper ocean to improve performance of numerical models , and constructing statistical tests for model validation based on realistic confidence intervals for estimated mean fields and appropriate quantitative misfit measures.

OBJECTIVES

The objectives for the first year of research were:

- to develop a prediction algorithm for Lagrangian trajectories and study its accuracy in terms of the drifter density and Lagrangian correlation time,

- to estimate the prediction errors from synthetic data and compare it with those of obtained by theoretical means,

- to understand effects of the compressibility and space correlation in the Lagrangian motion predictability,

- to develop an assimilation algorithm for estimating the entrainment velocities from sea surface tracer observations,

- to derive formulas for the mean square errors (MSE) of estimators of mean oceanic fields for both Eulerian and Lagarangian observations.

APPROACH

I develop theoretical approaches to the Lagrangian prediction , transport estimation and model validation problems in context of statistical inference for random processes and fields covered by stochastic partial differential equations. I design computational algorithms realizing developed mathematical methods. Together with my collaborators from Rosenstiel School of Marine and

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Atmospheric Research (RSMAS), we implement the algorithms in concrete ocean models such as MICOM , as well as carry out a statistical analysis of different data sets by means of new methods.

WORK COMPLETED

1. Lagrangian prediction.
2.

A prediction algorithm based on the Kalman filter approach was developed and an appropriate error analysis was proposed (Ozgokmen et al, 1999). The predictability of particle trajectories in oceanic flows was investigated in the context of a primitive-equation, idealized, double-gyre ocean model. The performance of the prediction scheme was quantified as a function of a number of factors: (i) dynamically-different flow regimes: interior gyre, western boundary current and midlatitude jet regions; (ii) density of drifter data used in assimilation; and (iii) uncertainties in the knowledge of the mean flow and the initial conditions. The data density was characterized by the number of data per degrees of freedom $N(R)$, defined as the number of drifters within the typical Eulerian space scale from the prediction particle.

Regarding to the space correlation and compressibility effects, an exactly solved one-dimensional stochastic model has been discovered (L.Piterbarg and V.Piterbarg, 1999). The asymptotical state of a Lagrangian particle ensemble was completely described as the correlation scale goes to zero.

2. Transport and mixing estimation.

An inversion technique for the ocean near-surface heat transport (Ostrovskii and Piterbarg 1995) was extended to accommodate the effect of the vertical heat flux at the bottom of the upper ocean mixed layer in (Ostrovskii and Piterbarg, 1999). We used the heat balance equation involved conventional parameterization of the vertical heat flux via entrainment into the mixed layer from the interior below during the mixed layer deepening. The equation was reduced to the regression estimator aimed on inversion of the sea temperature time series for the unknowns: vertical entrainment velocity, horizontal velocity and diffusivity, feedback factor, and atmospheric forcing parameter. The regression estimator was applied to the time series of vertical profiles of temperature anomalies compiled from the COADS and the World Ocean Atlas 1994 on 10-day mean basis over the spatial grid of 2° longitude and 1° latitude in two regions of the North Pacific: 1) near the ocean western boundary east of Japan and 2) between the Hawaiian islands and California for the winter season (December-March) during 1965 - 1990.

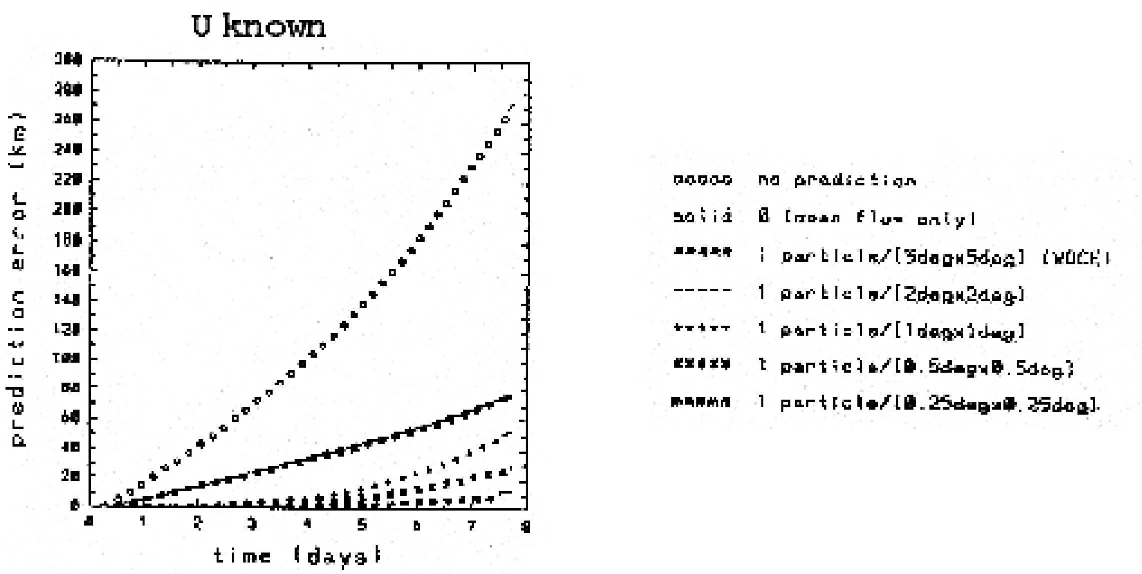
A comprehensive review of recent results and methods in estimation of stochastic partial differential equations (SPDE) with oceanographic applications was given in (Piterbarg, 1999). The surface tracer inversion problem was considered in line with last advances in the SPDE estimation theory.

3. *Model validation.*

Explicit formulas for the MSE’s of the mean flow estimators were obtained for different scenarios of Eulerian and Lagrangian velocity measurements in terms of the observation step, observation time, and fluctuation intensity. The dependence of the estimation accuracy on the velocity field time-space scales was studied.

RESULTS

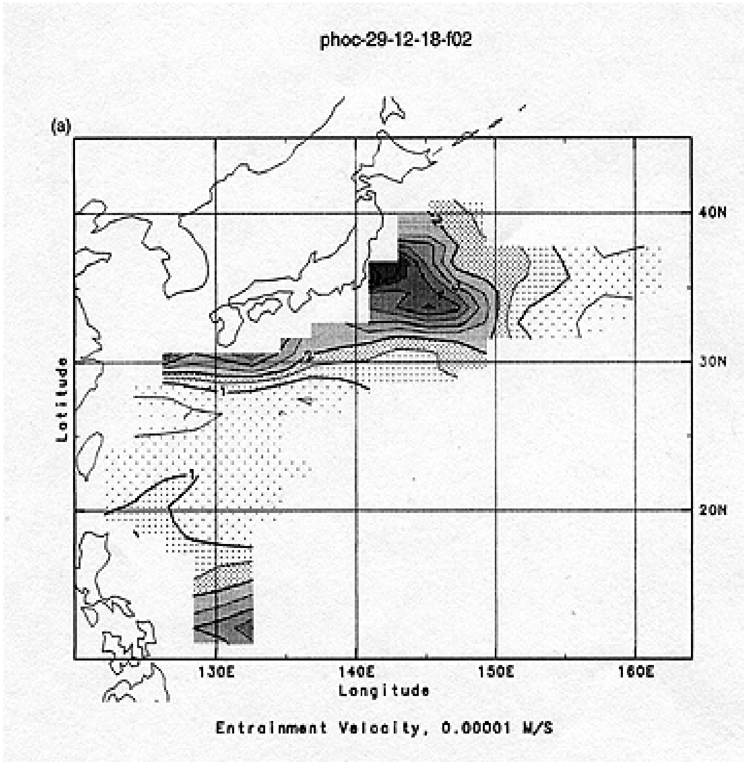
1. The prediction simulations showed that quite accurate predictions are achieved in all regions over the Lagrangian time scale when *N(R) > 1.* The prediction error decreases sharply as the particle density increases and may be as small as 10 km for the 1 week prediction even in very active zones (Fig. 1). Even when the mean flow field and initial turbulent velocities are not known accurately, the information derived from the surrounding drifter data is shown to compensate when *N(R) > 1.* Theoretical formulas showed good agreement with the numerical results and hence they may serve as useful a-priori estimates of Lagrangian prediction error for practical applications.



1. Dependence of the prediction error on time for different drifter densities in the western boundary current.

A theoretical analysis of the Lagrangian motion in a compressible flow showed that an initial particle continuum tends to form tight clusters as the Eulerian correlation radius goes to zero. The distance between clusters was found to have the Raleigh distribution. The average number of clusters per length unit is equal to $1/\sqrt{\pi D t}$, where t is the observation time and D is the diffusivity.

2. The entrainment velocities found by means of SST inversion were of the order of 0.00001 m/sec. The entrainment effect is particularly significant in the Kuroshio-Oyashio frontal zone (Fig.2). The model skill is also substantially enhanced in this region: the inversion yields more realistic features of the Kurosio transport as compared with our previous study, which neglected the vertical heat flux.



2. Entrainment velocities extracted from the SST data and temperature vertical profiles.

3. Here I present only one example regarding to the mean Eulerian velocity estimation. Namely, the constant velocity is measured by M moorings spaced with interval Δr during long time T. It is supposed that the velocity fluctuations are described by a white noise of intensity D. The confidence intervals are completely determined by the mean square error

$$MSE = \frac{D\gamma_{\alpha}}{TM^{1-\alpha/2}(\Delta r \cdot k)^{2-\alpha}}$$

where α is the slope of the fluctuation space spectrum, k is the maximal wave number, and γ is a constant depending on α.

IMPACT/APPLICATIONS

1. This is the first time that the predictability limits for Lagrangian particles have been estimated. The estimates and methodology can be applied for planning rescue operations on the sea and tentative forecasting pollution spreading .

The theoretical results on the Lagrangian motion in the compressible short-correlated flow imply some interesting features in a tracer distribution on the sea surface. In particular, an initial tracer distribution with a constant gradient evolves to a strip-like structure observed often on the sea surface.

2. The estimation of the entrainment velocities in our study is novel and it can stimulate further efforts in the inversion other sea surface tracers such as chlorophyll for vertical fluxes in the ocean.

3. The accurate expressions for MSE in the mean flow estimation allow us to conclude how much is the confidence in the mean ocean filelds found from observations. Further similar studies for fields coming from numerical models would give a basis for statistically significant comparison of model outputs and observations.

TRANSITIONS

The prediction algorithm and the error theory were and will be used in RSMAS to study the Lagrangian predictability for other synthetic and real data sets. The SST inversion algorithm moved with my co-author A. Ostrovskii to the Frontier Observational Research System for Global Change JAMSTEC (Tokyo, Japan) where it will be used for processing different SST data sets.

RELATED PROJECTS

1. "Predictability of Particle Trajectories in the Ocean", ONR, PI T.Ozgokmen (RSMAS),

2. "Lagrangian Data Analysis in Mesoscale Prediction and Model Validation Studies", ONR, PI A.Griffa (RSMAS)

3. "Circulation of Marginal and Semi-Enclosed Seas (Modeling Support for CREAMS II in the Japan (East) Sea", ONR, PI C.Mooers

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